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Ultra-Low-Power Wireless

Ultra-Low Power Wireless SoCs Enabling a Batteryless IoT

Dr. Benton Calhoun and Dr. David Wentzloff
co-CTOs
August 2015

Today's IoT… is messy

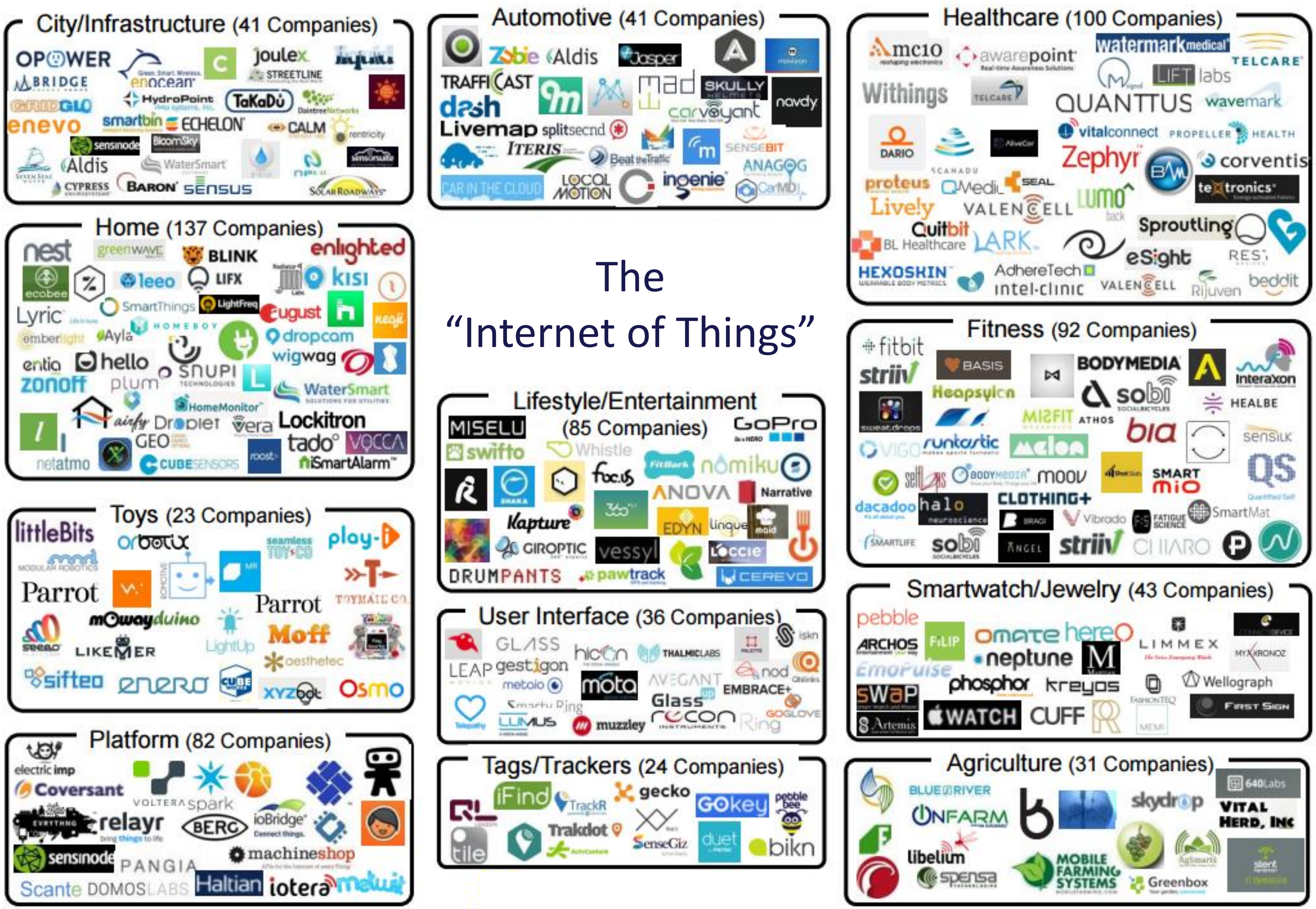

Figure from venturescanner.com

Today's IoT… is limited by hardware

Most wireless IoT devices use:

- … MCU at 10s of MHz and 1s of mA
- … Radio at 5-10s of mA (e.g. BLE)
- … Battery
- … Active power in 10s to 100s of mW
- … Achieve "Low Power" by duty cycling, or turning OFF for large fractions of time →

Limited in functionality *or* lifetime

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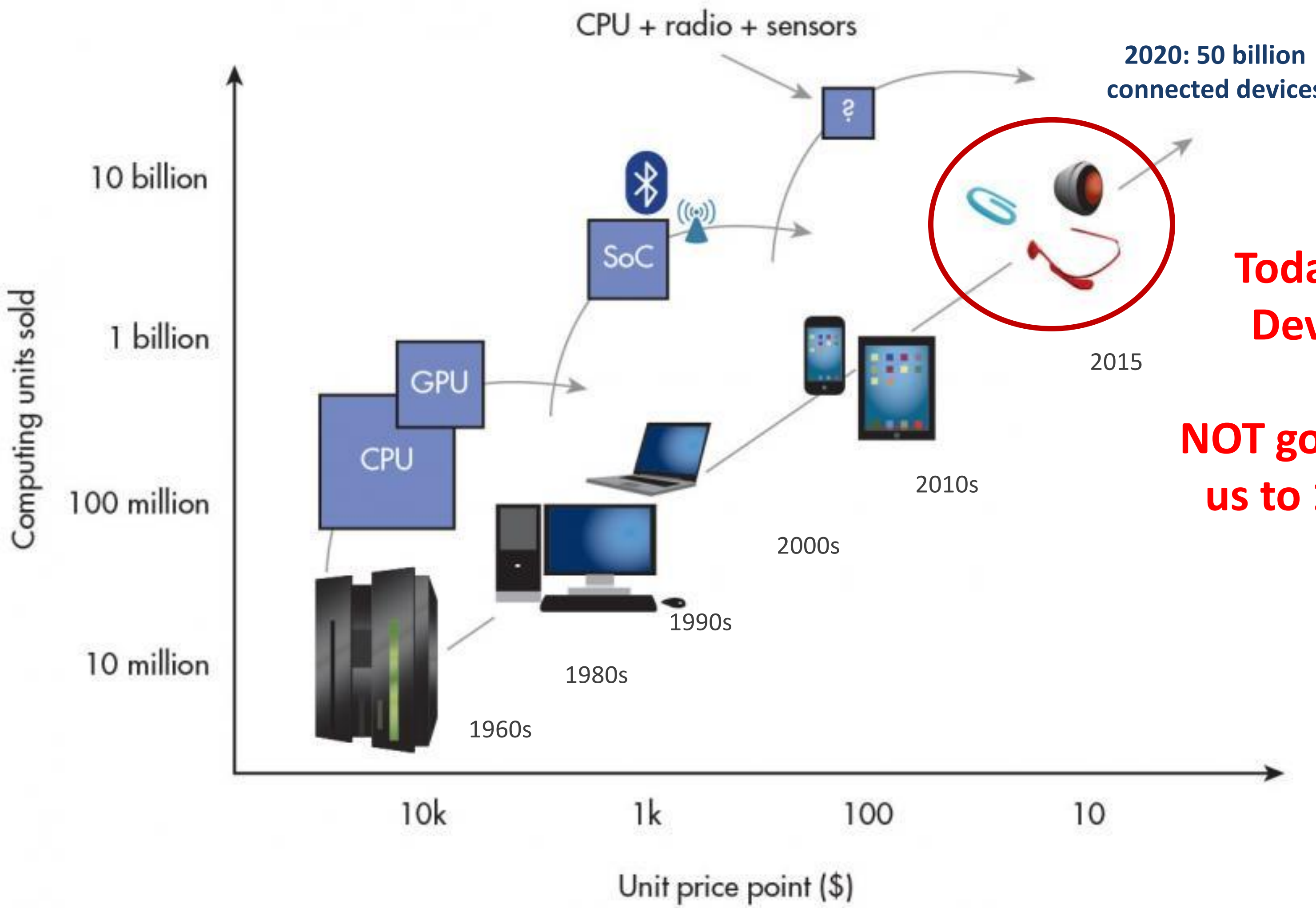
Next Wave of Computing: "Internet of Things"

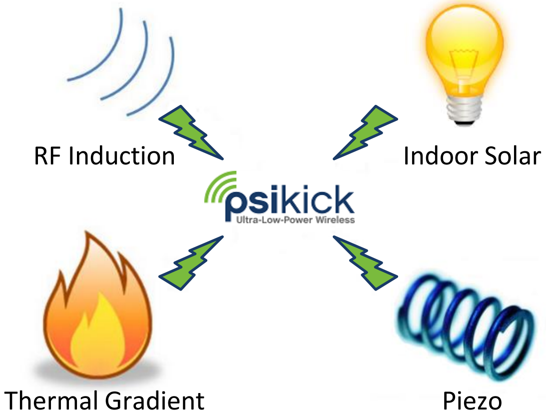
2025: 1 trillion wireless sensors



Today's IoT Devices –

NOT going to get us to 1 Trillion

Powering 1 Trillion Sensors...



BATTERIES

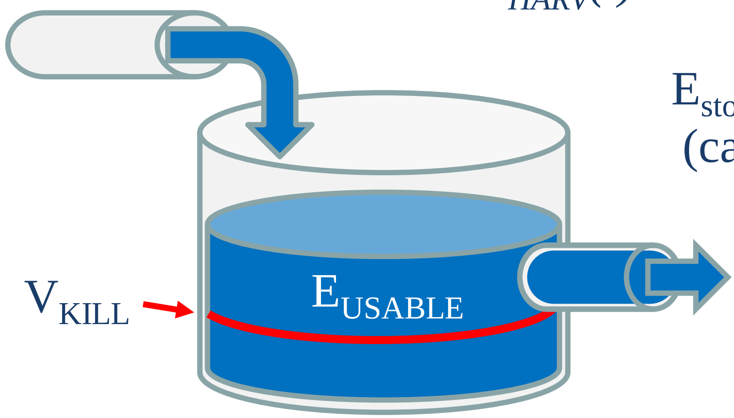
- Today's RF ICs = 10s to 100s mW ACTIVE
- with current batteries → hours/days/months
- No "Moore's Law" for energy density
- **1T x 10 yr. batteries = 275M replacements/recharges per day**

ENERGY HARVESTING

- **THE ANSWER**, but...
- It only delivers **10s of µWs / cm²**
- Versus 10s to 100s of mWs
- Need 2-3 order of magnitude improvement
- **So, power target of 20-30 µWs**

Need wireless SoCs @ 1/1000th of today's power consumption

Self-powered Operation



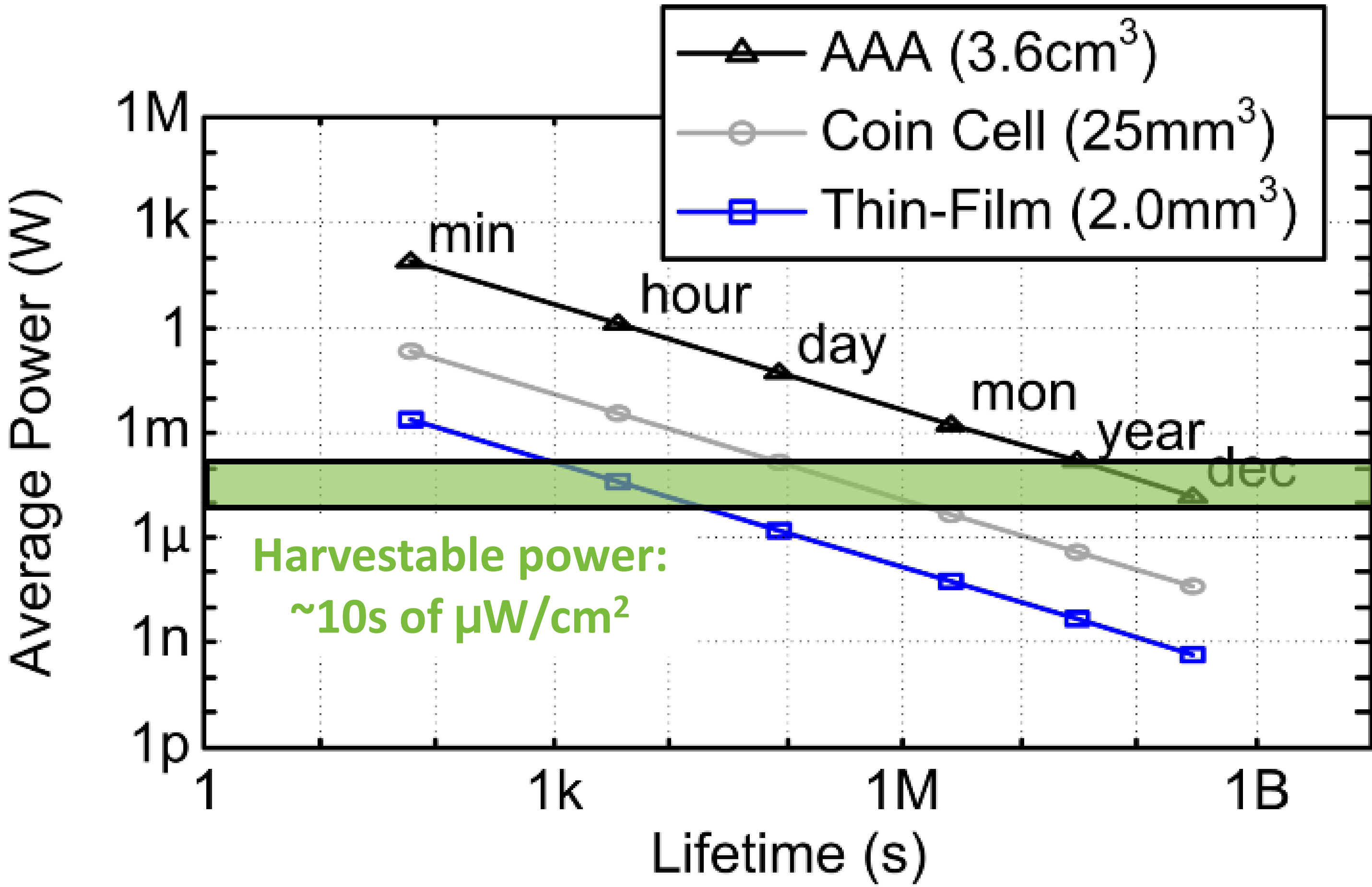
P_{LOAD} may exceed P_{HARV} for some time periods

Constraint on power used over any time period:

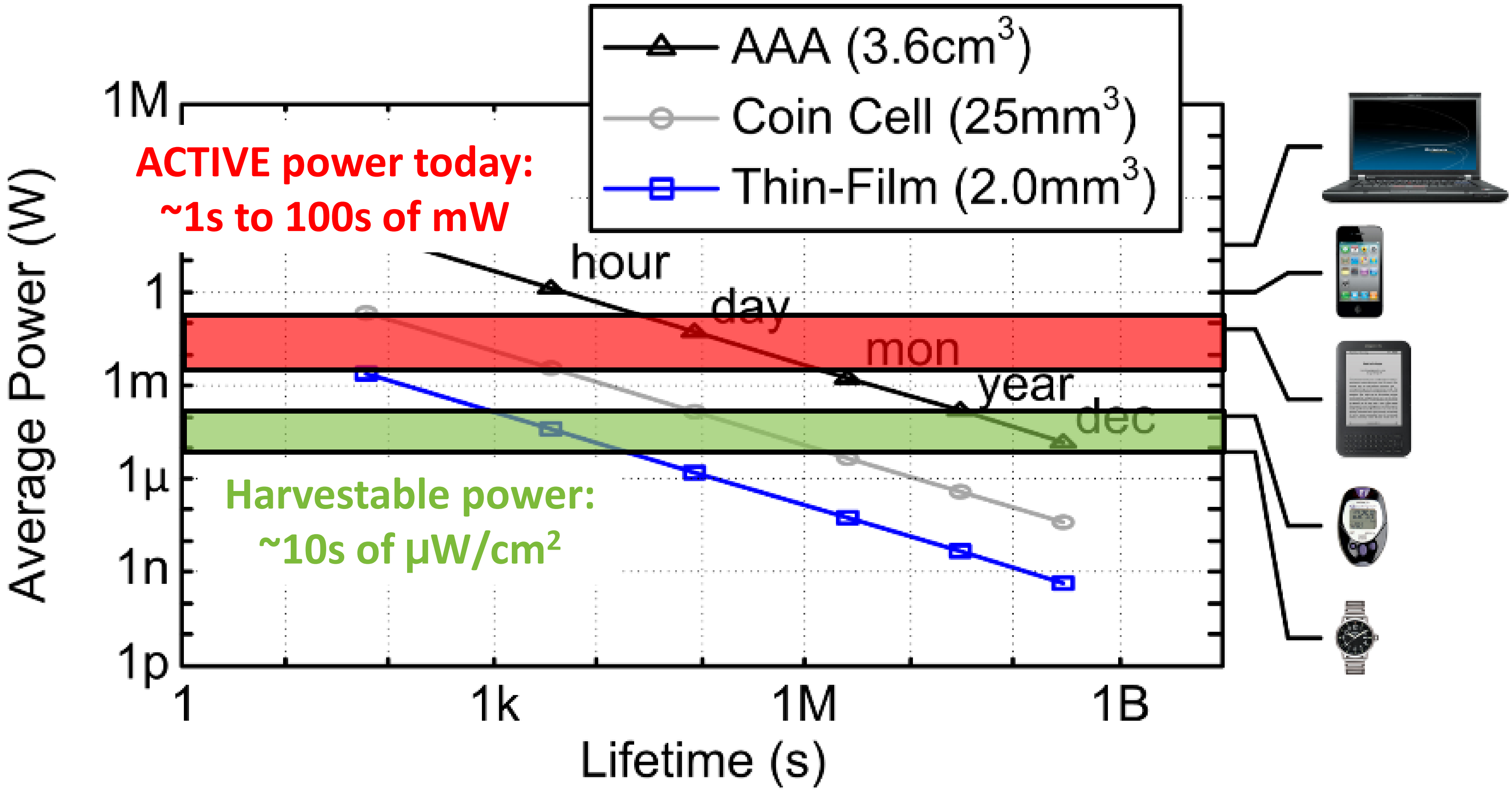
$$\forall t, \quad E_{USABLE} \geq \int_0^t [P_{LOAD}(t) - P_{HARV}(t)]dt$$

Good: $P_{HARV} \uparrow$ $E_{storage} \uparrow$ $P_{LOAD} \downarrow$

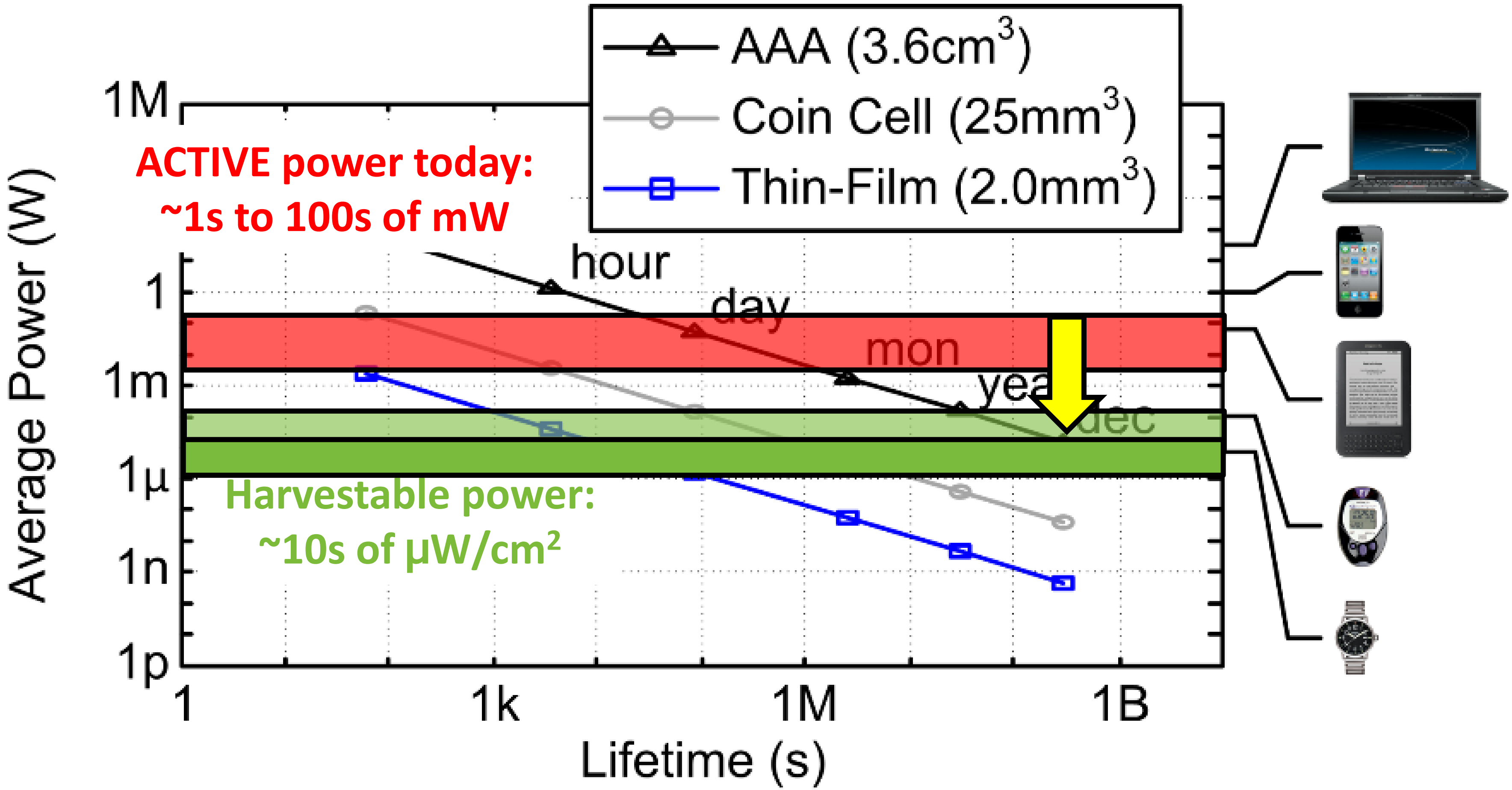
Power Limitations for IoT



Power Limitations for IoT



Power Limitations for IoT



Need to reduce power active power by ~1000X to < 20-30μW

What can you do with 20 – 30 μW ACTIVE power?

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Agenda

- Proof of Concept: Self powered University SoCs
- Self-powered Wakeup Radio
- Self-powered SoC for the IoT

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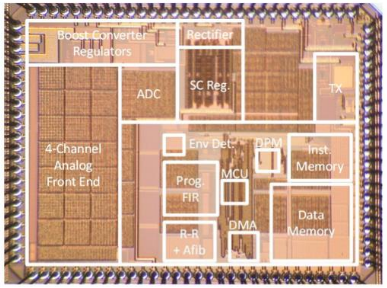
What can you do with 20 – 30 µWs?   A lot.

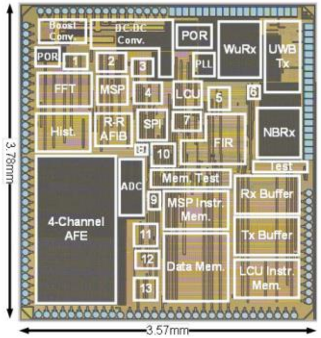
19 µW Wearable ECG / EEG / EMG



- Wearable ExG
  - Continuous ECG
  - Extract heart rate intervals
  - Detect atrial fibrillation
  - RF updates every ~3-5s
  - Powered by body heat with Thermoelectric Generator
  - No battery

- 19 µW total ACTIVE power
- ISSCC 2012

6.46 µW Wireless Activity Monitor



- Activity Monitor Demo:
  - 3-axis accelerometer data
  - Extract posture, activity
  - Build histogram of activity Stream raw data over TX (10m range)
  - Harvest from PV with MPP tracking and 75% efficiency end-end
  - No battery

- 6.46 µW total power
- ISSCC 2015

Approach to Achieving Ultra Low Active Power

Key breakthroughs in...

Digital Sub-Threshold Circuit Operation

- Low-voltage, sub-threshold digital circuits
- Devices are “off”, resulting in 10X power savings

+

Low-Power RF Expertise

- Extremely low power radio frequency
- 10+ years developing low-power/high-performance RF

+

System-level Integration

- Tight system integration dramatically improves efficiency
- “Un-blocks”
- Understand and optimize for ***lowest joules per operation***

...resulting in a new paradigm of circuit design

Trade-offs

- **RF Range** – sweet spot between 1 m and 4 km; data rate between 1 Mb/s and 1 kb/s
- **Processor Speed** – sweet spot between 100s kHz and 10s MHz

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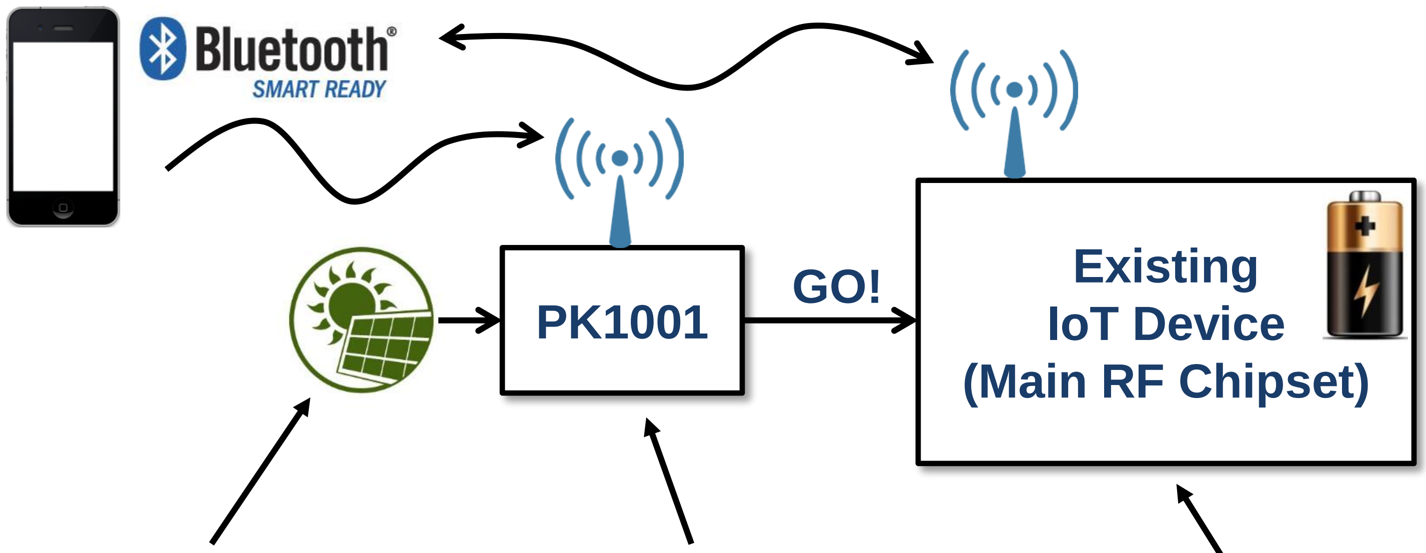
Self Powered Wakeup Chip (PK1001) Application



1. PK1001 powered from a harvested energy source and charges an energy storage device

2. RF signal addressing detected. PK1001 issues interrupt to Main RF chipset

3. Main RF chipset communicates with handset. Decides when to go to sleep

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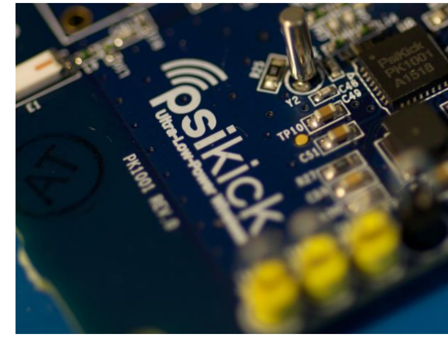
PK1001 Main Features



- World’s lowest-power wake-up radio solution
  - A self-powered wireless trigger
  - ~500nW ACTIVE system power measured
    - No radio duty cycling
  - 3-7 meter wireless range
  - Retrofit existing IoT devices to reduce power from mW to <500nW
- PK1001 includes:
  - Boost converter with cold start for energy harvesting
  - SIMO DC/DC buck for full chip power management
  - Wakeup receiver for 433/915/2.4G ISM bands with programmable code
  - 32kHz crystal oscillator
  - Interrupt handler with SPI interface
- Wirelessly wake up from programmable code or BLE signal

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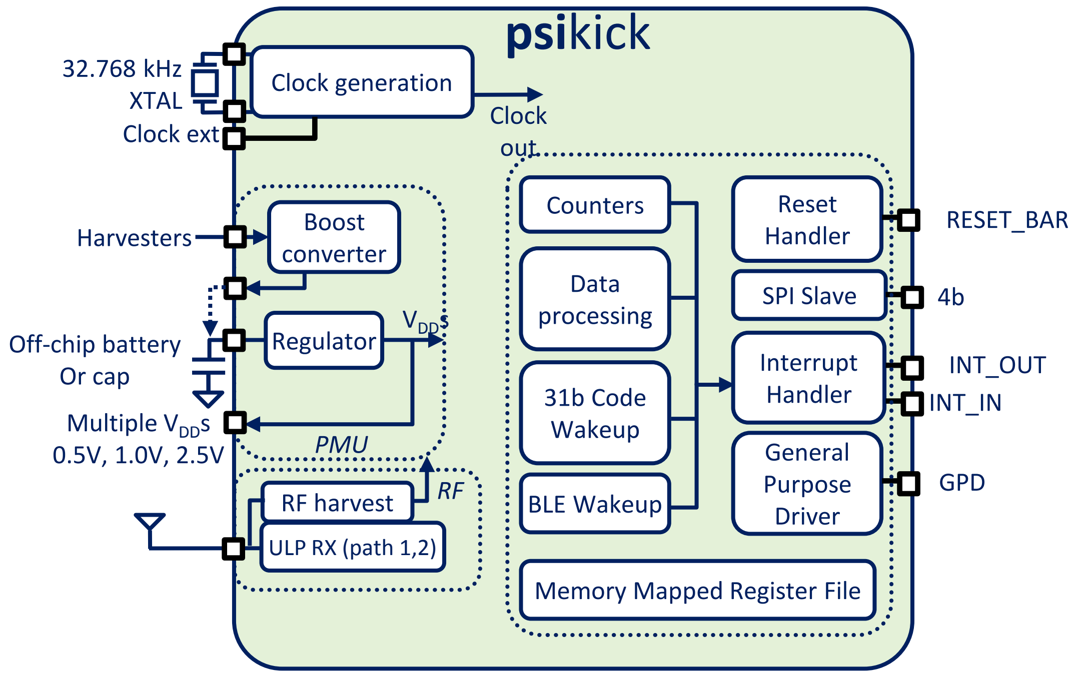
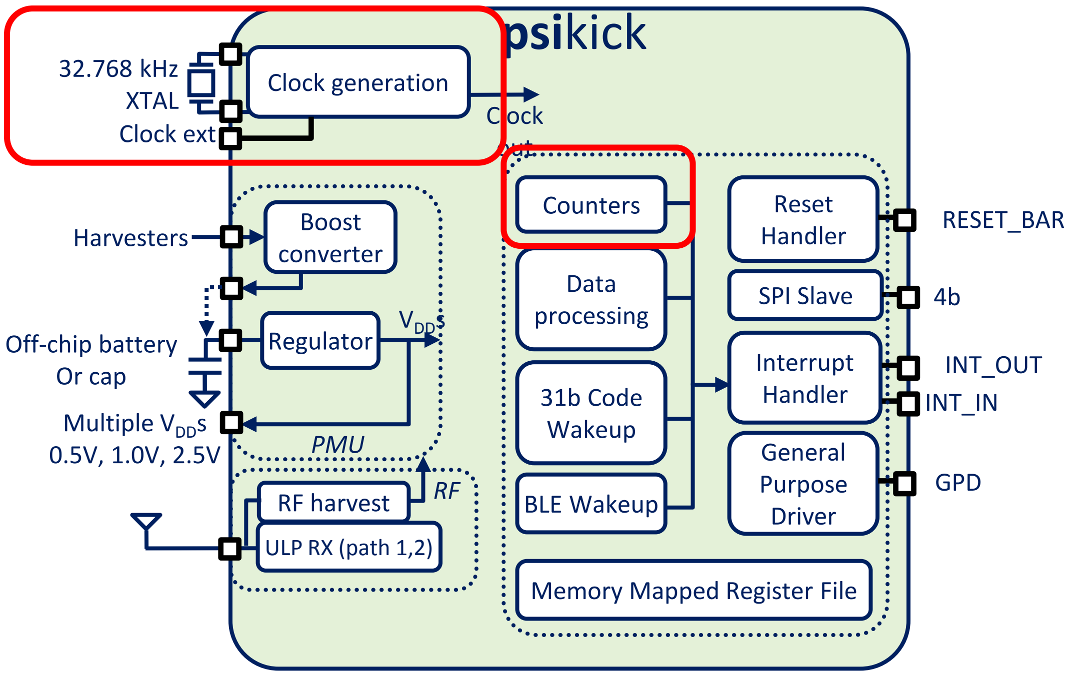
Block Diagram of Wakeup Radio Chip



Block Diagram of Wakeup Radio Chip

Clock Gen: 32kHz clock with counters for interrupt generation and time keeping



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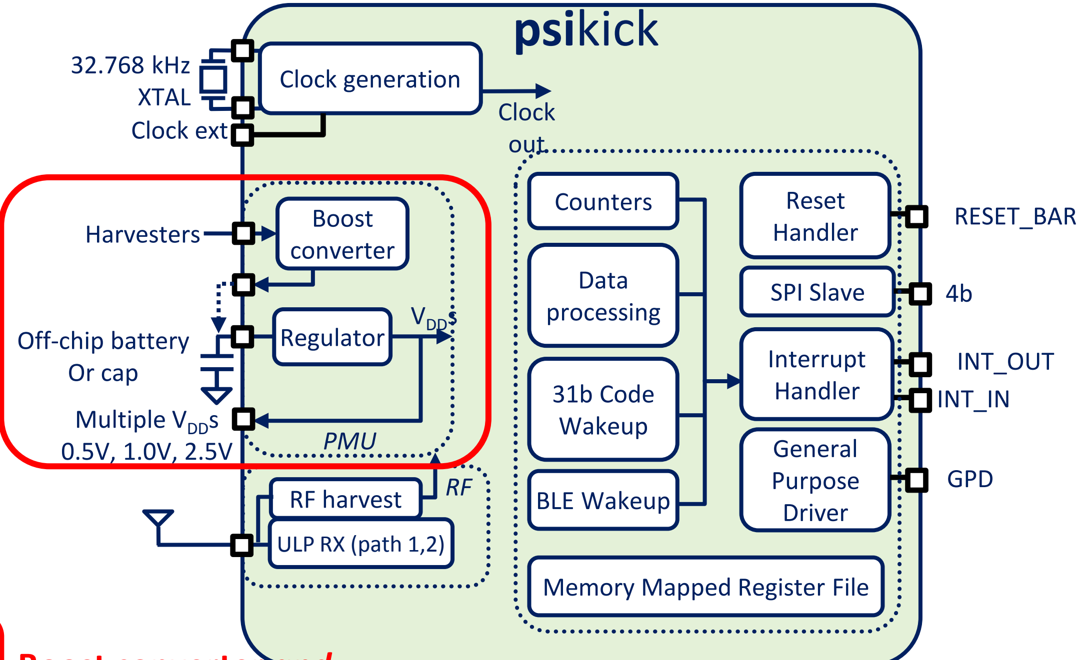
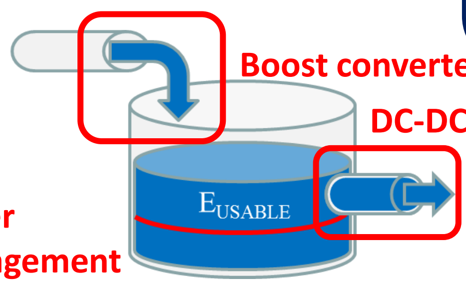


Boost converter *and* DC-DC regulator are both integrated



Power management

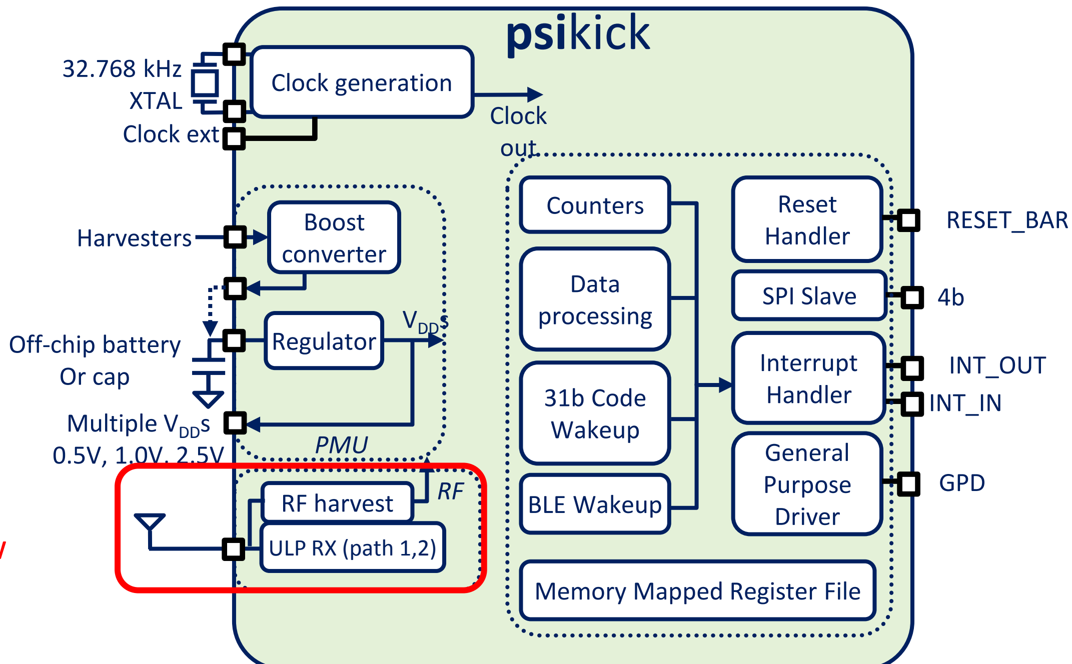
Off-chip Cap

Block Diagram of Wakeup Radio Chip

Clock Gen: 32kHz clock with counters

Energy Harvesting-Power Management Unit (EH-PMU): harvest from solar, TEG. Regulate 3 rails.

Wakeup Receivers: Low sensitivity (100nW, ~-42dBm) and medium sensitivity modes (200nW, ~-55dBm); RF harvester.



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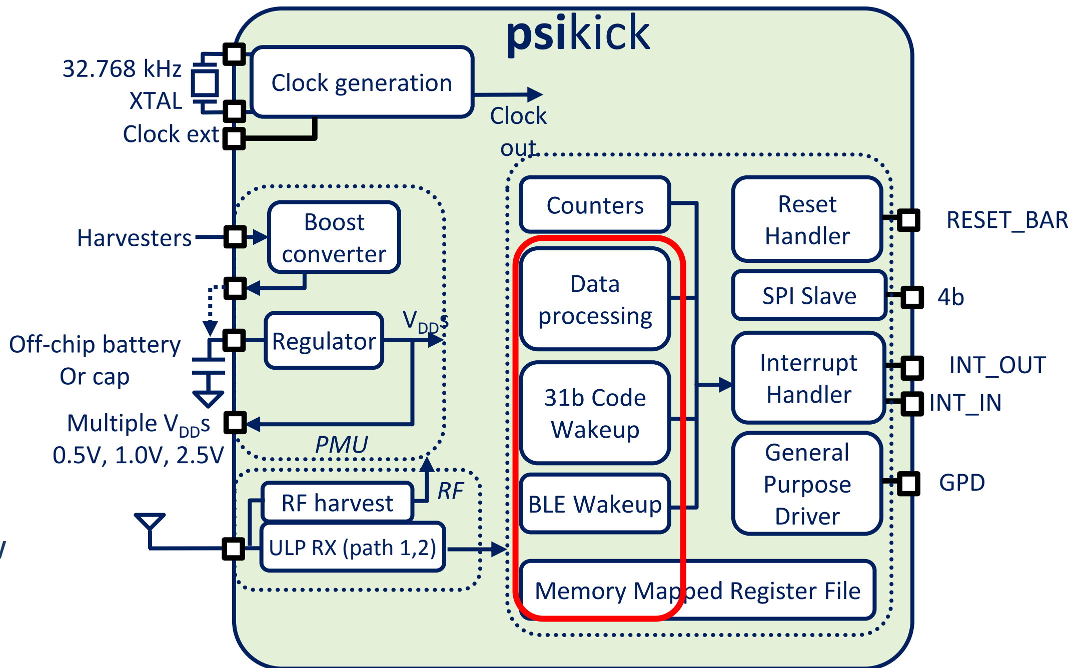

Wakeup Options: Wakeup from BLE or 31b Codes. Programmable addresses. Packet based reception.

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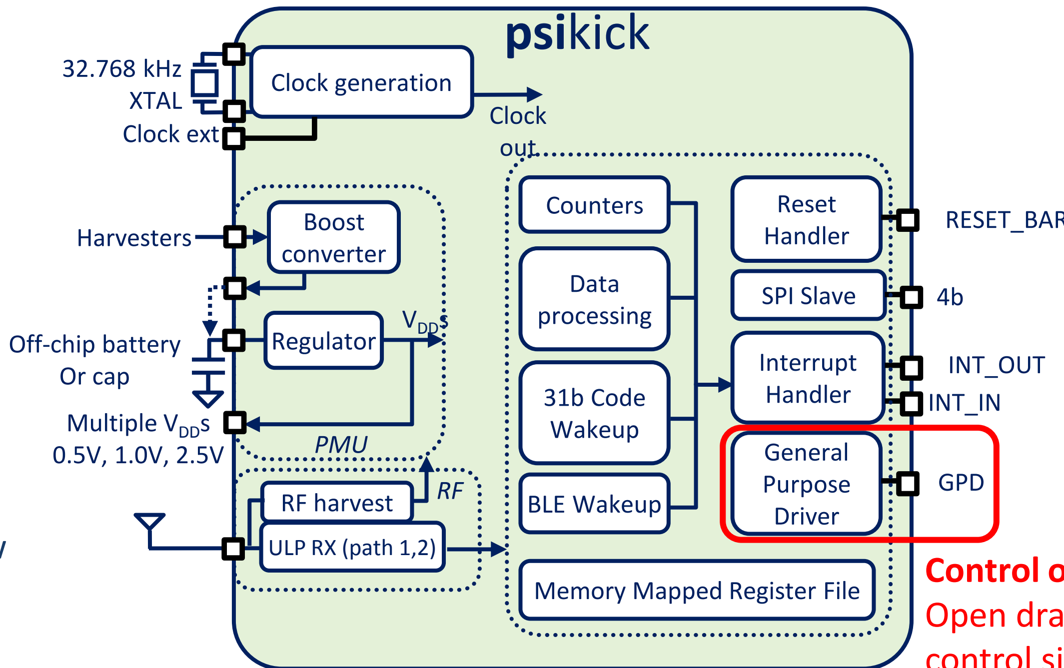

Control off-chip power FET with GPD: Open drain driver used to pull down a control signal to drive a power FET off chip.

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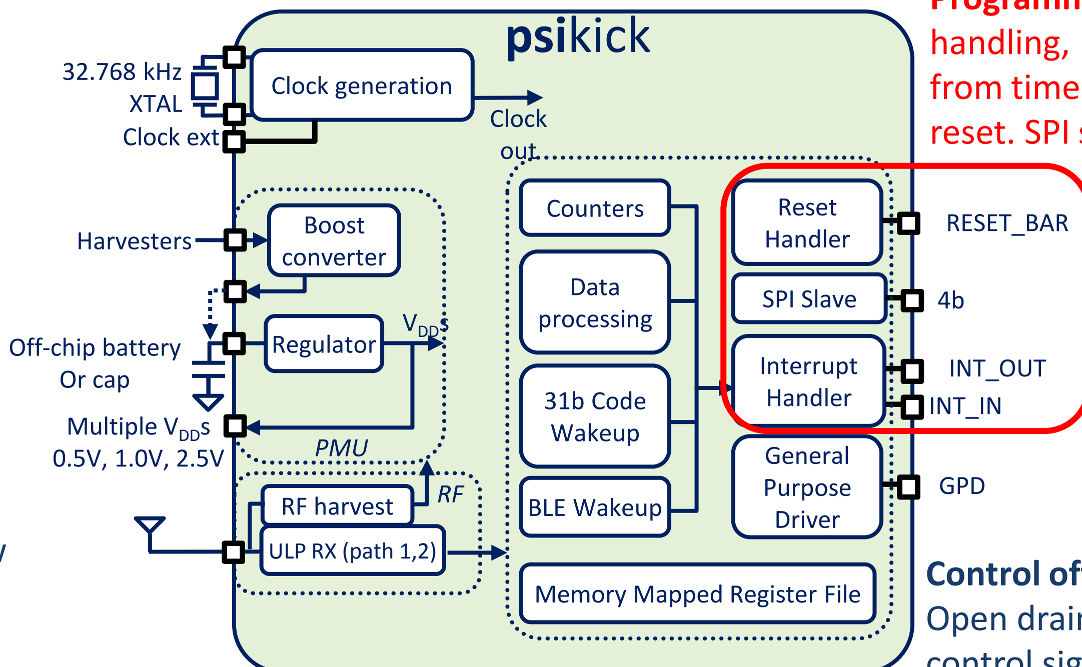


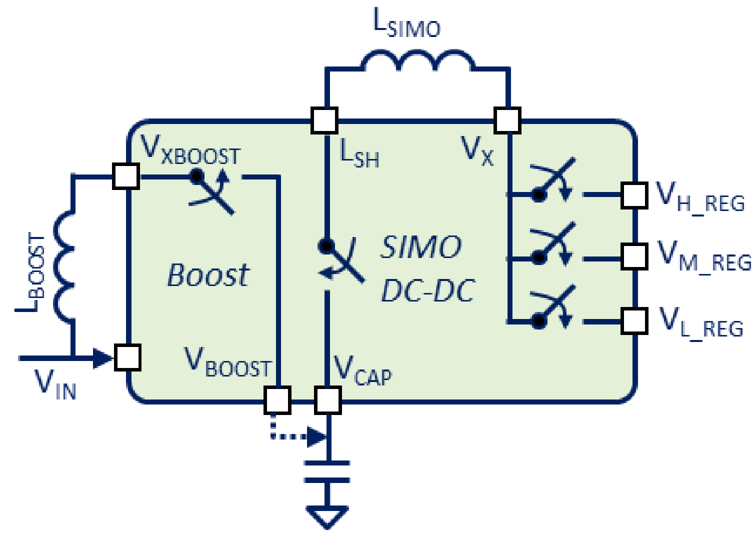
Programmable Peripherals: Interrupt handling, programmable interrupts from timer, RF, external, brown-out, reset. SPI slave for low power I/O.

Control off-chip power FET with GPD: Open drain driver used to pull down a control signal to drive a power FET off chip.

Wakeup Options: Wakeup from BLE or 31b Codes. Programmable addresses. Packet based reception.

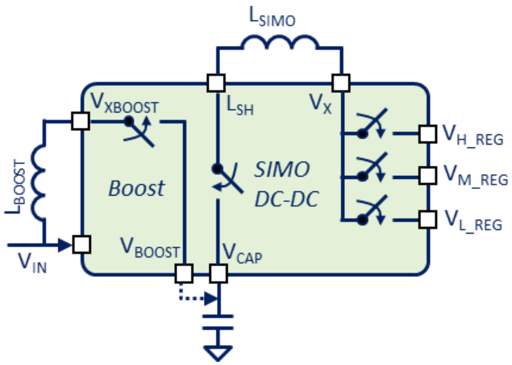
EH-PMU Conceptual Design

- **Energy harvesting**
  - **Diverse power source options:**
    - **Harvested energy (solar, TEG, RF)**
    - **Rechargeable battery: 0.8 V to 5 V**
  - **Boost converter stores up to 5 V on off-chip storage capacitor or rechargeable battery**
  - **Integrated maximum power point tracking (MPPT)**
  - **Minimum 30mV input voltage**
  - **RF kick-start**
  - **Boost cold-start from <400mV**
- **Power Management Unit (PMU)**
  - **Single inductor, multiple output (SIMO) VDDs: 2.5V, 1.0V, and 0.5V**
  - **Active current: 350nA (function of V_{CAP})**

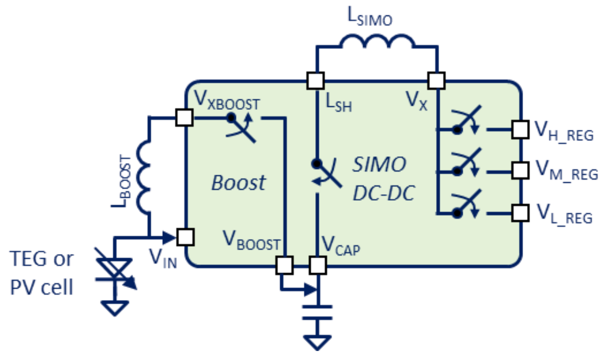


EH-PMU Operating Configurations

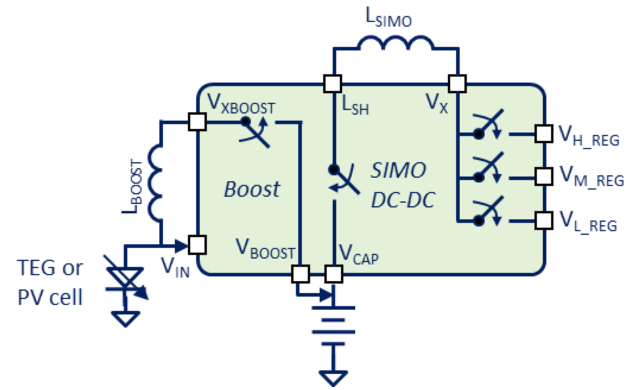
- **EH-PMU configurations:**



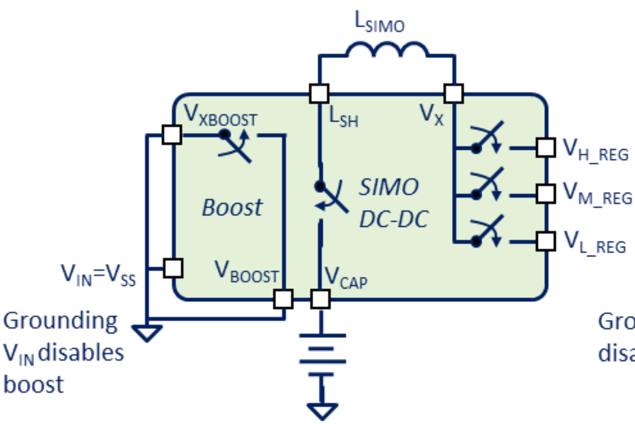
PMU structure



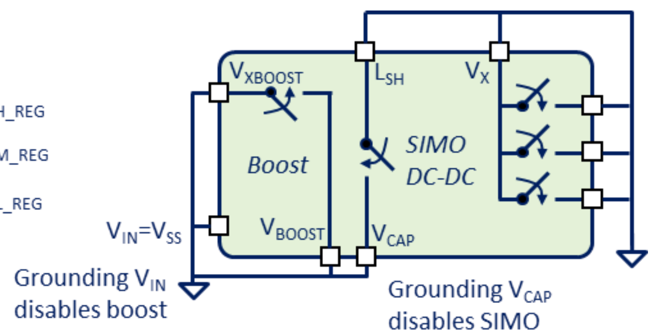
Harvesting Mode



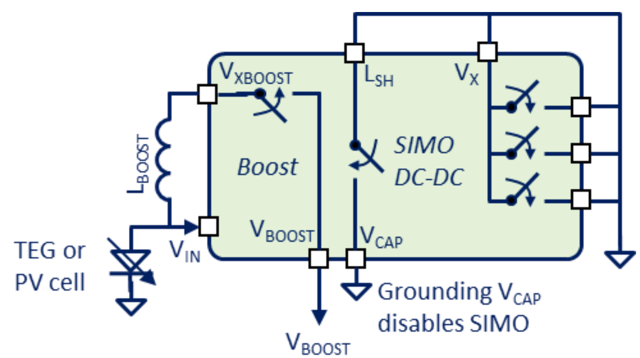
Charge Battery Mode



Battery Mode



No PMU Mode



Boost-only Mode

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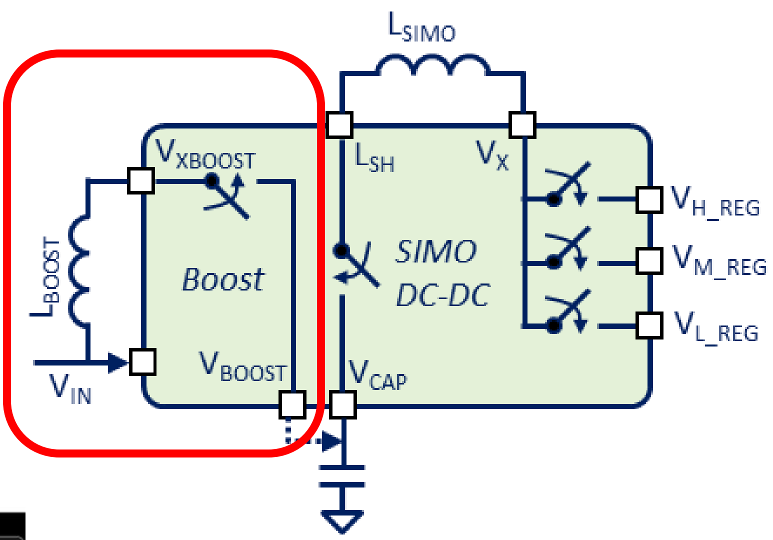
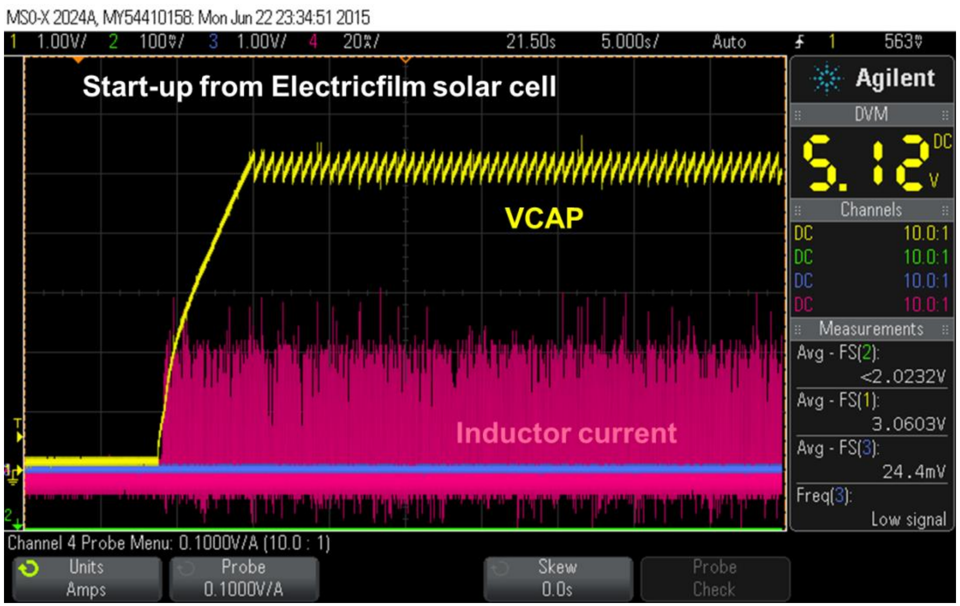
Energy Harvester Measured Results

- **Boost Converter**



- **Startup from Solar Cell**



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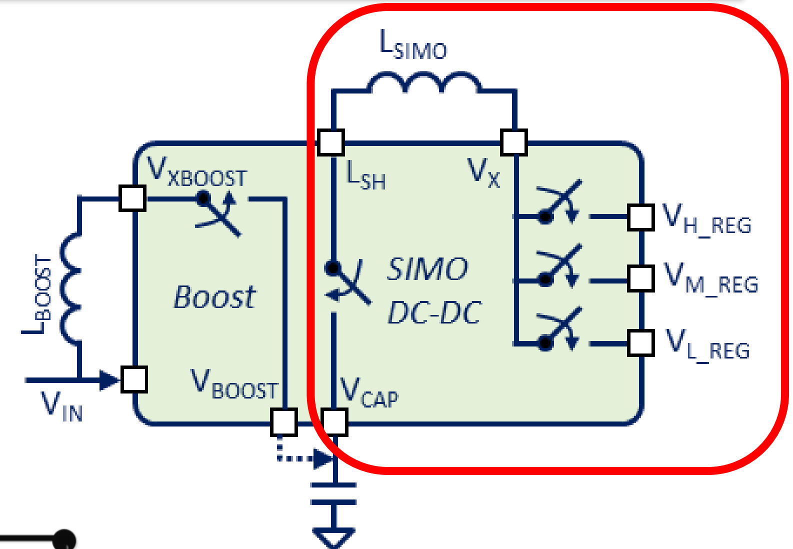
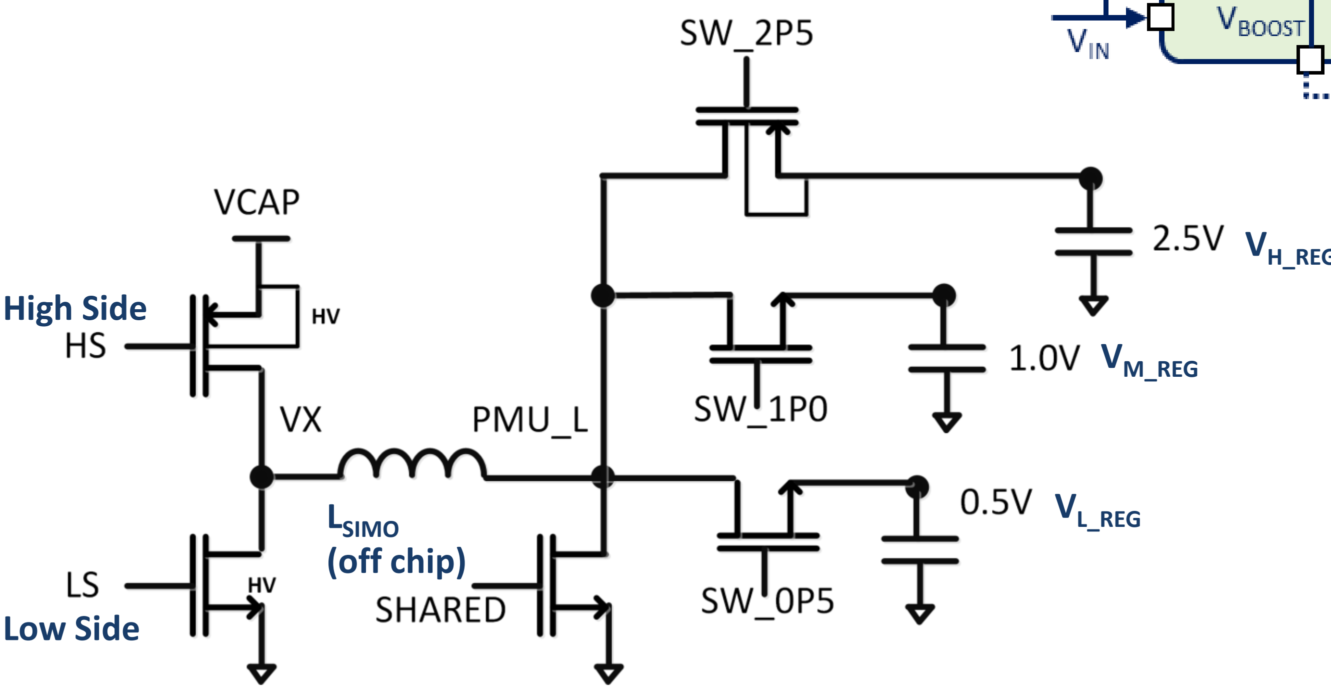
PMU Circuit Design

- **Buck / Boost SIMO Architecture**
- **1 shared inductor (off chip)**





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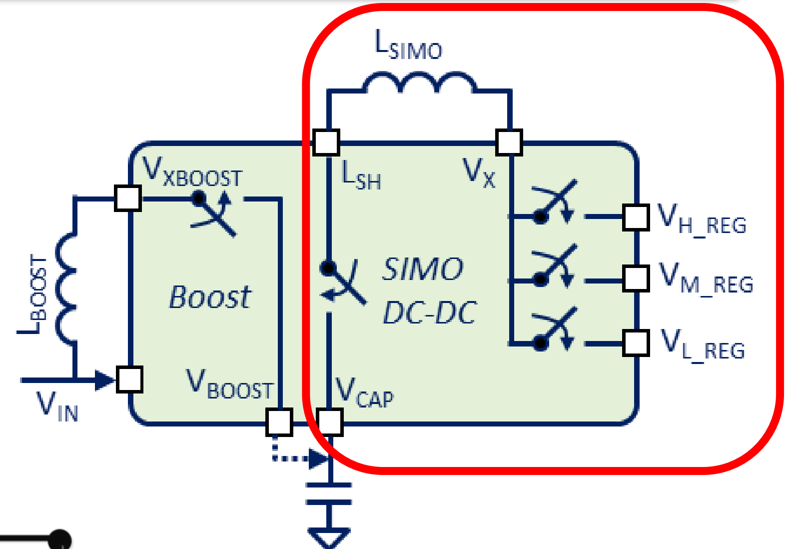
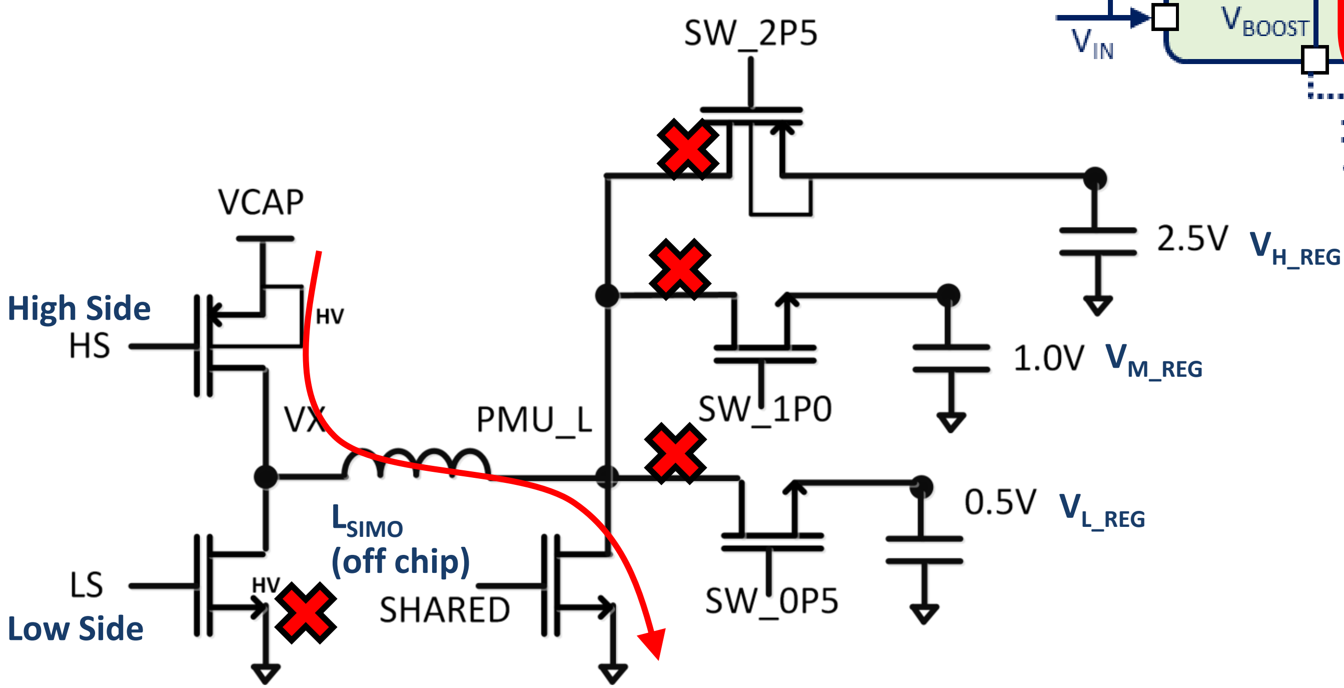
PMU Circuit Operation

- Buck / Boost SIMO Architecture
- 1 shared inductor (off chip)





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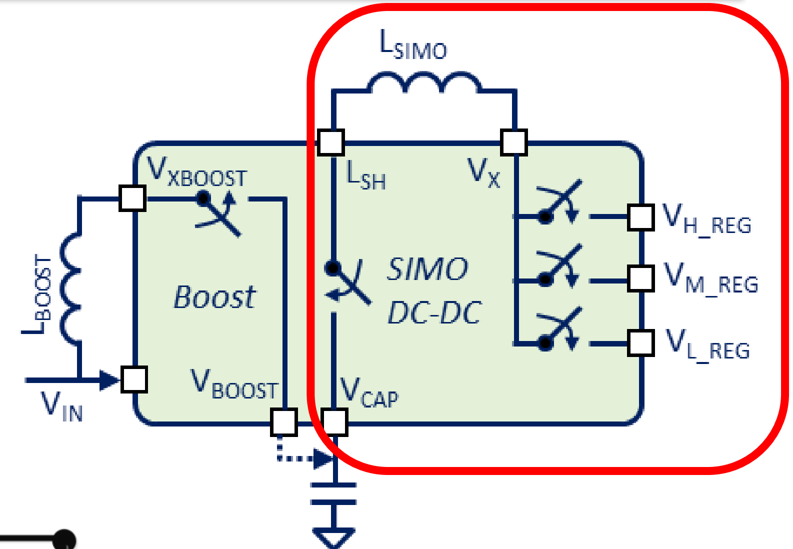

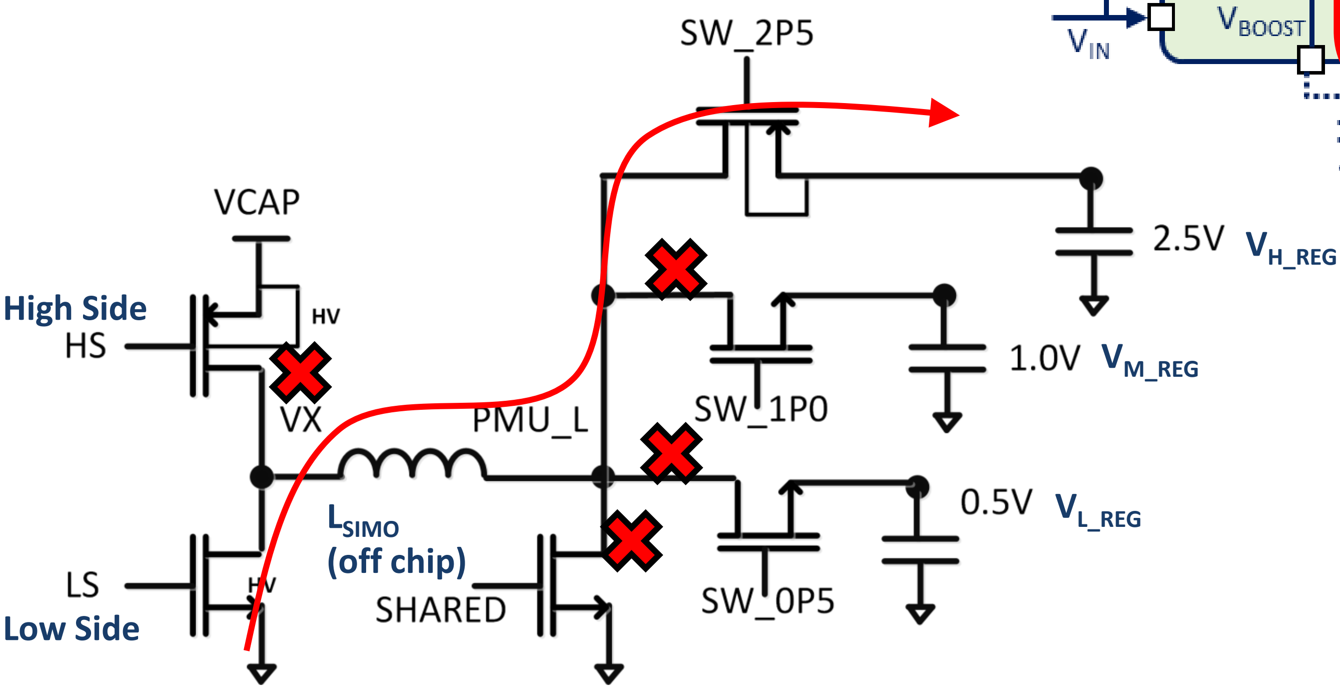

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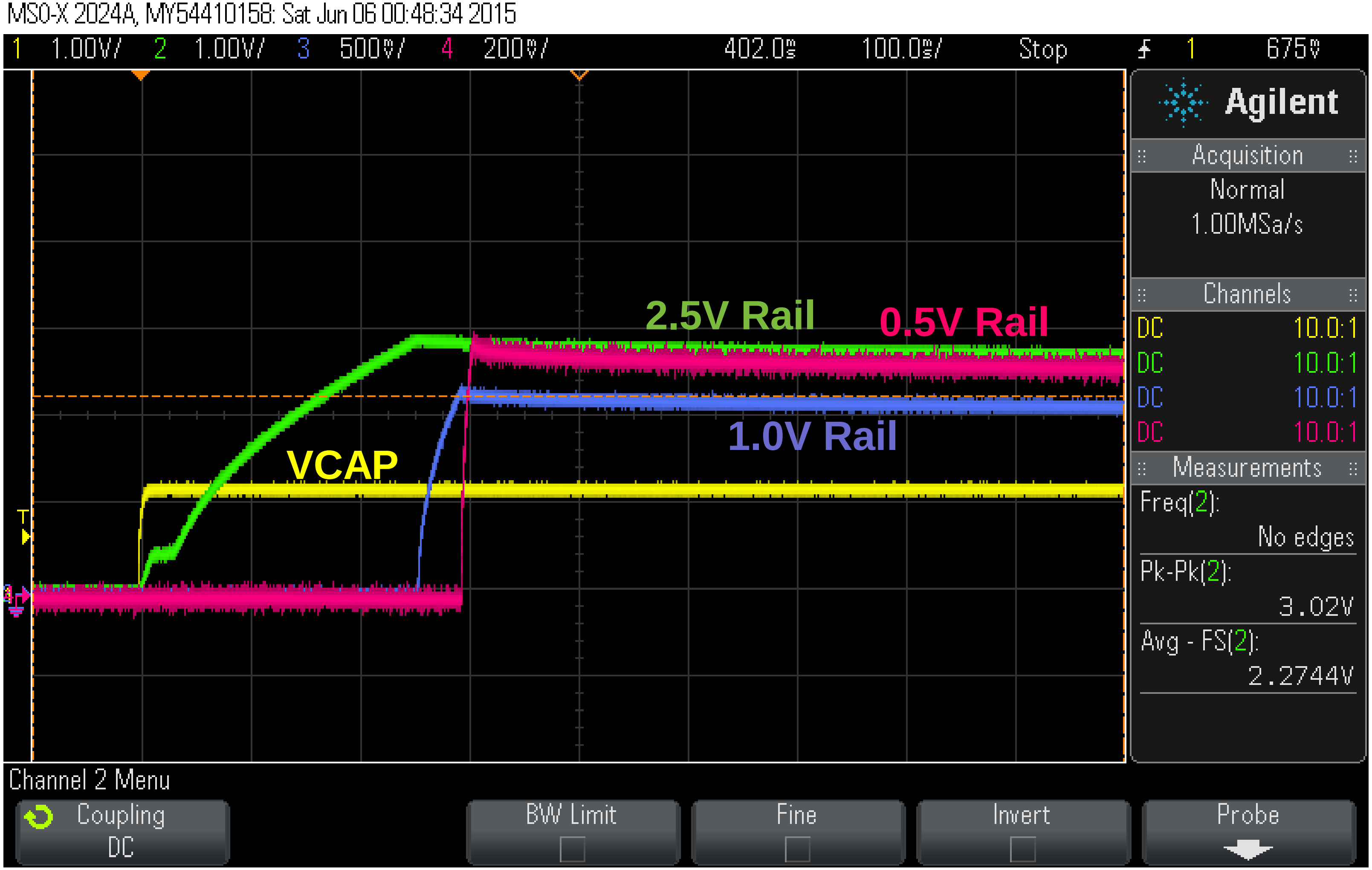
PMU Measured Startup



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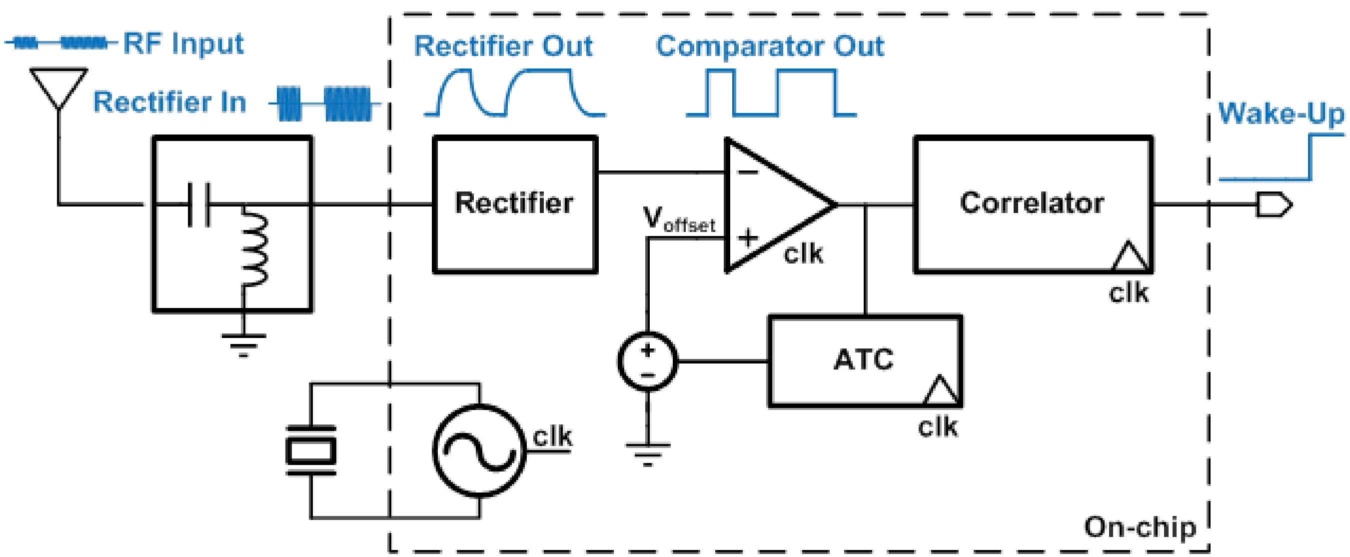
Wakeup Receiver Conceptual Design

- **Wakeup Receiver concept**
  - Off chip matching network selects frequency
  - Auto Threshold Control (ATC) to tune out interferers
  - Parallel correlators to match with stored codes or programmable BLE sequence



RF Format and Protocols

- Base modulation format: On-off keying (OOK)
- Three modes of operation
  - 31-bit code wake up
    - Single-code or multi-code sequence for wakeup
  - Receive mode
    - 802.15.4 packet format (min length)
    - 8-bit packet payloads
  - Wakeup from BLE mode

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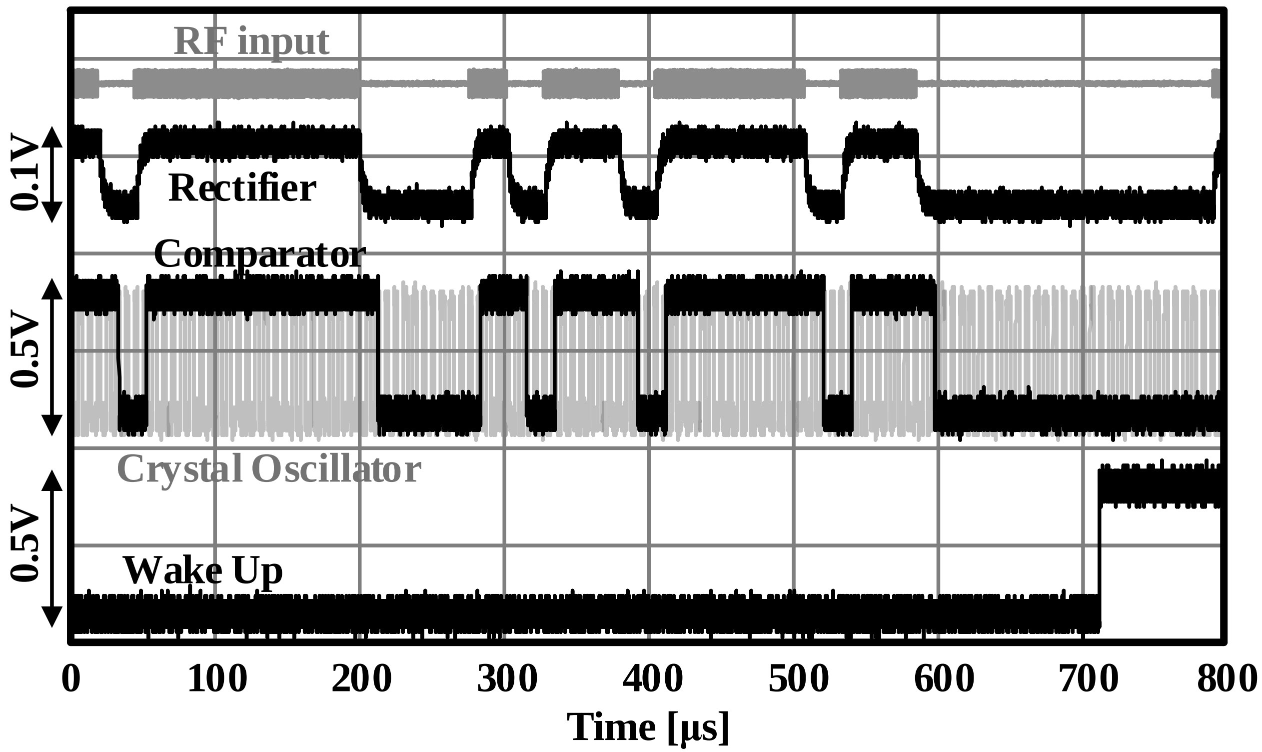
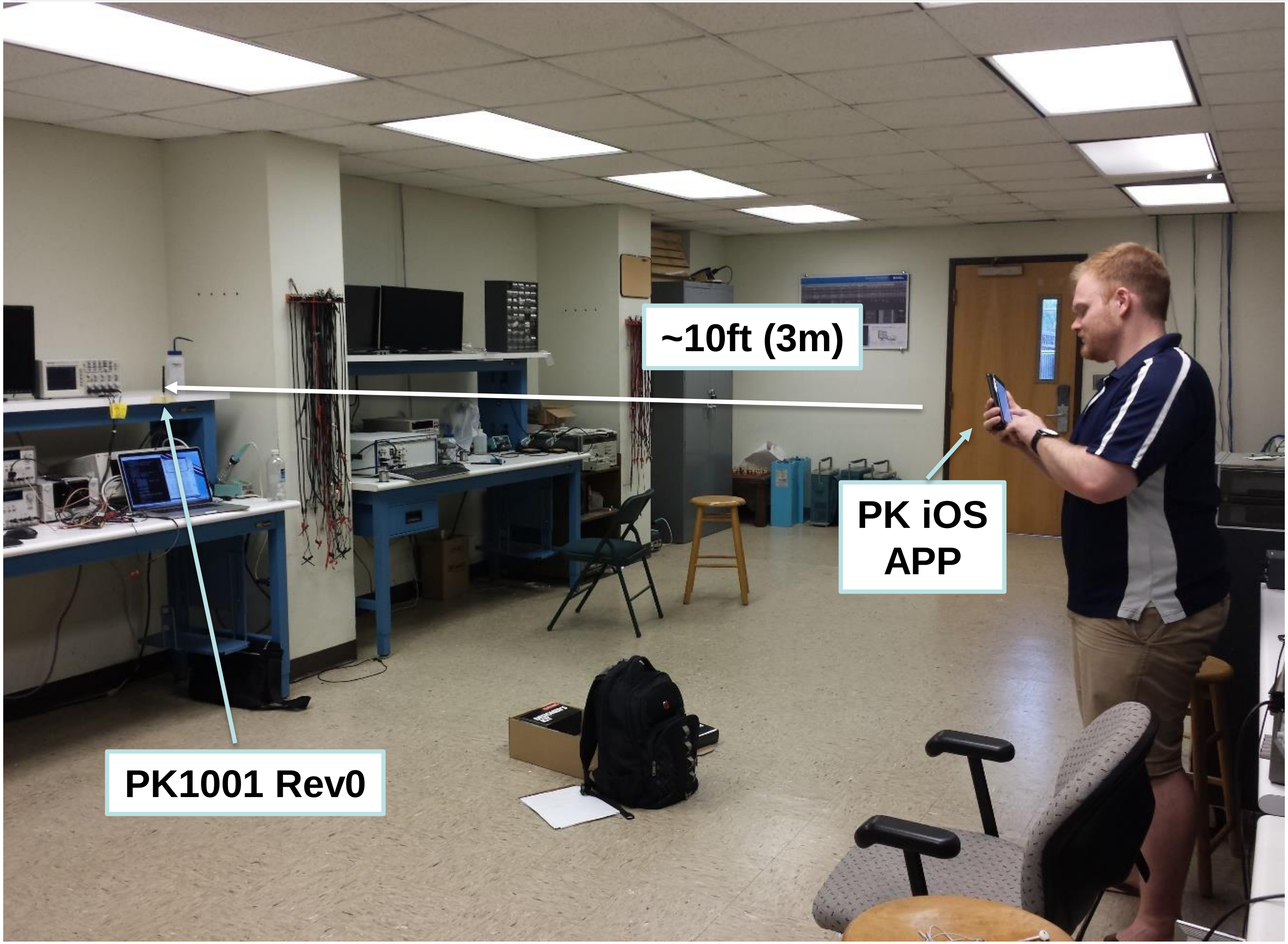
Wakeup Receiver Functionality

- **Measured waveforms showing function of Wakeup Radio**



PK1001 BLE Wakeup Demo



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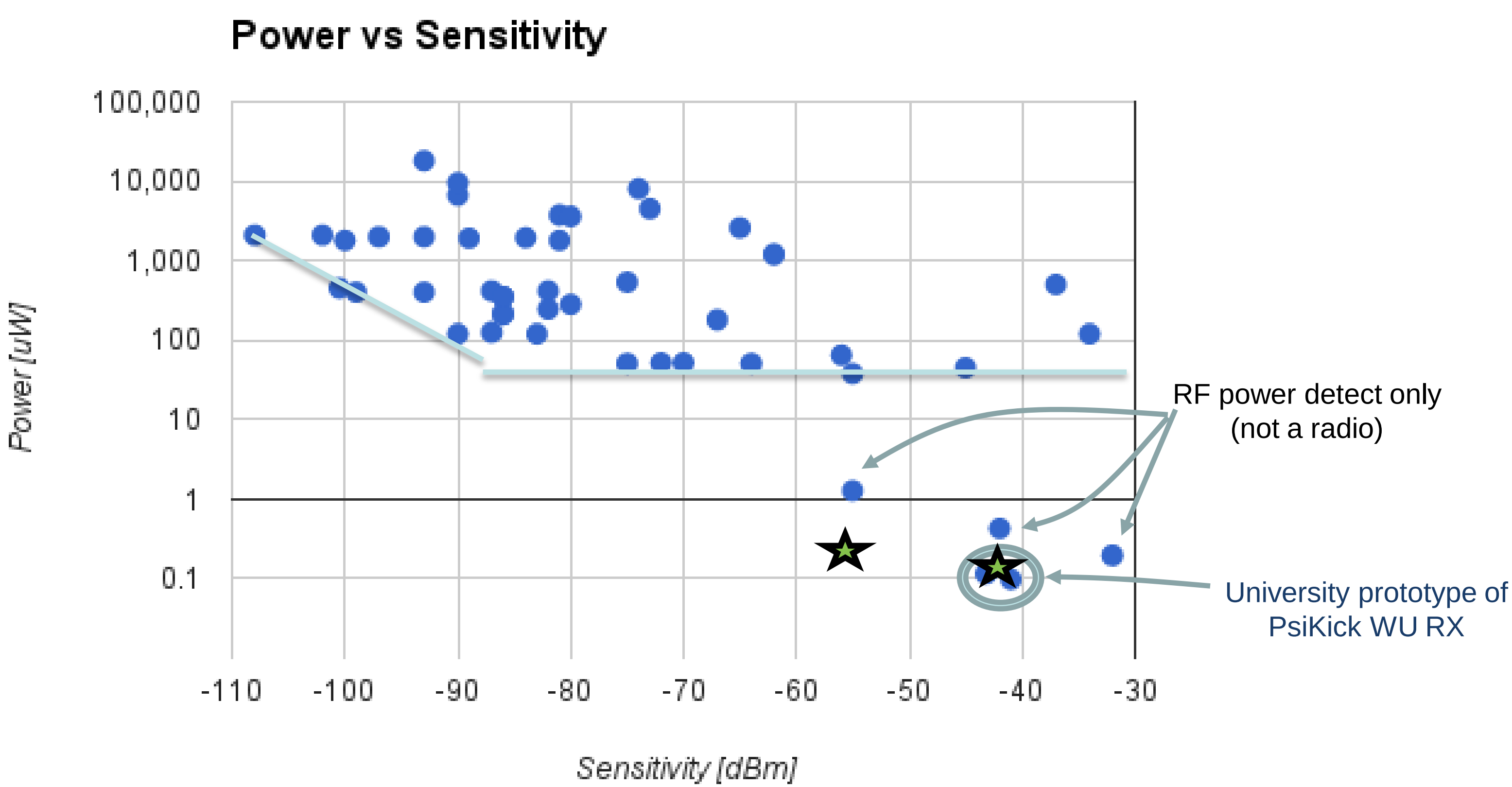
Wakeup Radio Benchmarking

- ## Sensitivity vs. Power

★ **PsiKick RX on PK1001**



Wentzloff, Umich - http://wwweb.eecs.umich.edu/wics/low_power_radio_survey.html

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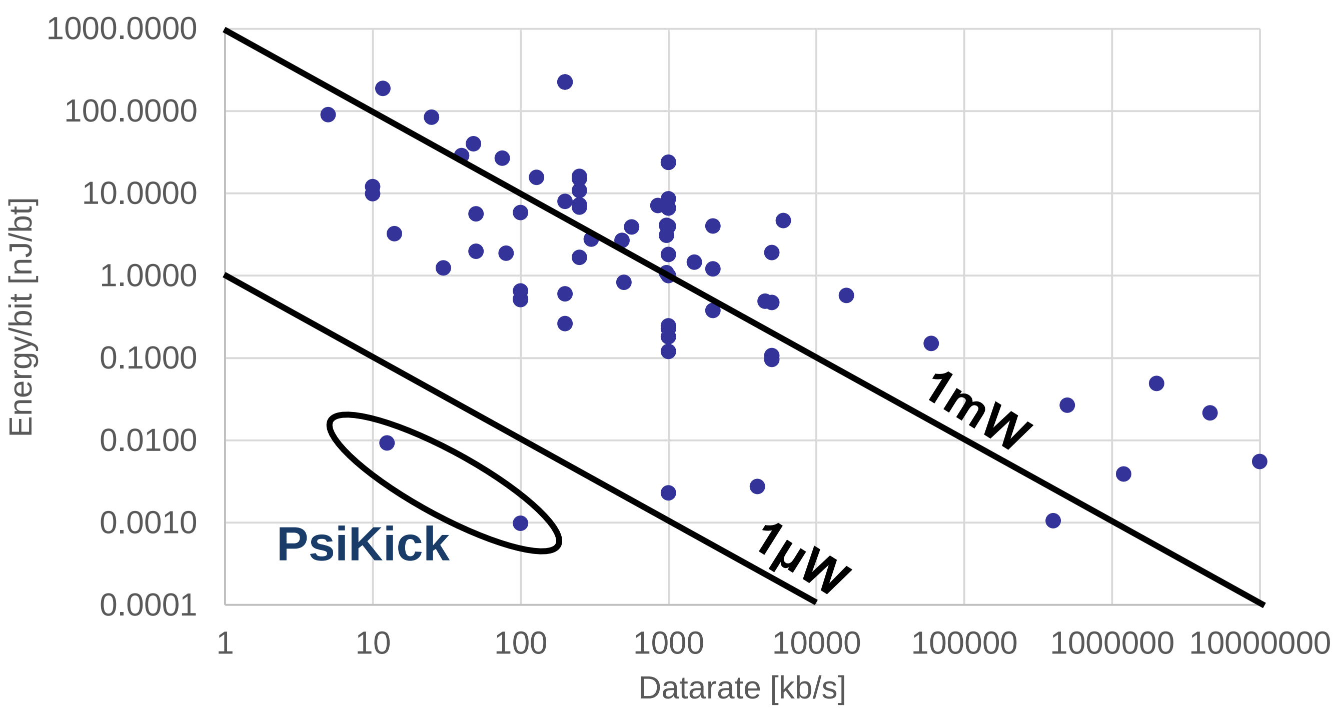
Energy Efficiency Tradeoff

- High data rates often lead to lower energy/bit
  - But higher active power (E/b * datarate)
- PK broke the 1µW floor, maintaining efficiency



PK1001 Measured Performance Summary

PK1001 Summary of Results				
	Spec	**Value**		**Unit**
Radio	Frequency	2.4		GHz
	Bit Rate	8.192		kbps
	Power	103	235	nW
	Sensitivity*	-40	-56	dBm
	Estimated Range (Tx = 0dBm)	1	6.3	meters
Energy-Harvesting	Standby power	350		nA
	Peak efficiency (Boost converter)	97		%
	Harvester input voltage level	30-2500		mV
	Max. Output Voltage	5		V
Power Management	SIMO , 3 output voltages	2.5V, 1.0V, and 0.5V		
	Efficiency	80		%
	Maximum Output load	50		mW

* Sensitivity calculated as lowest signal power to receive correct 31-bit code. Not 10^{-3} BER.

Agenda

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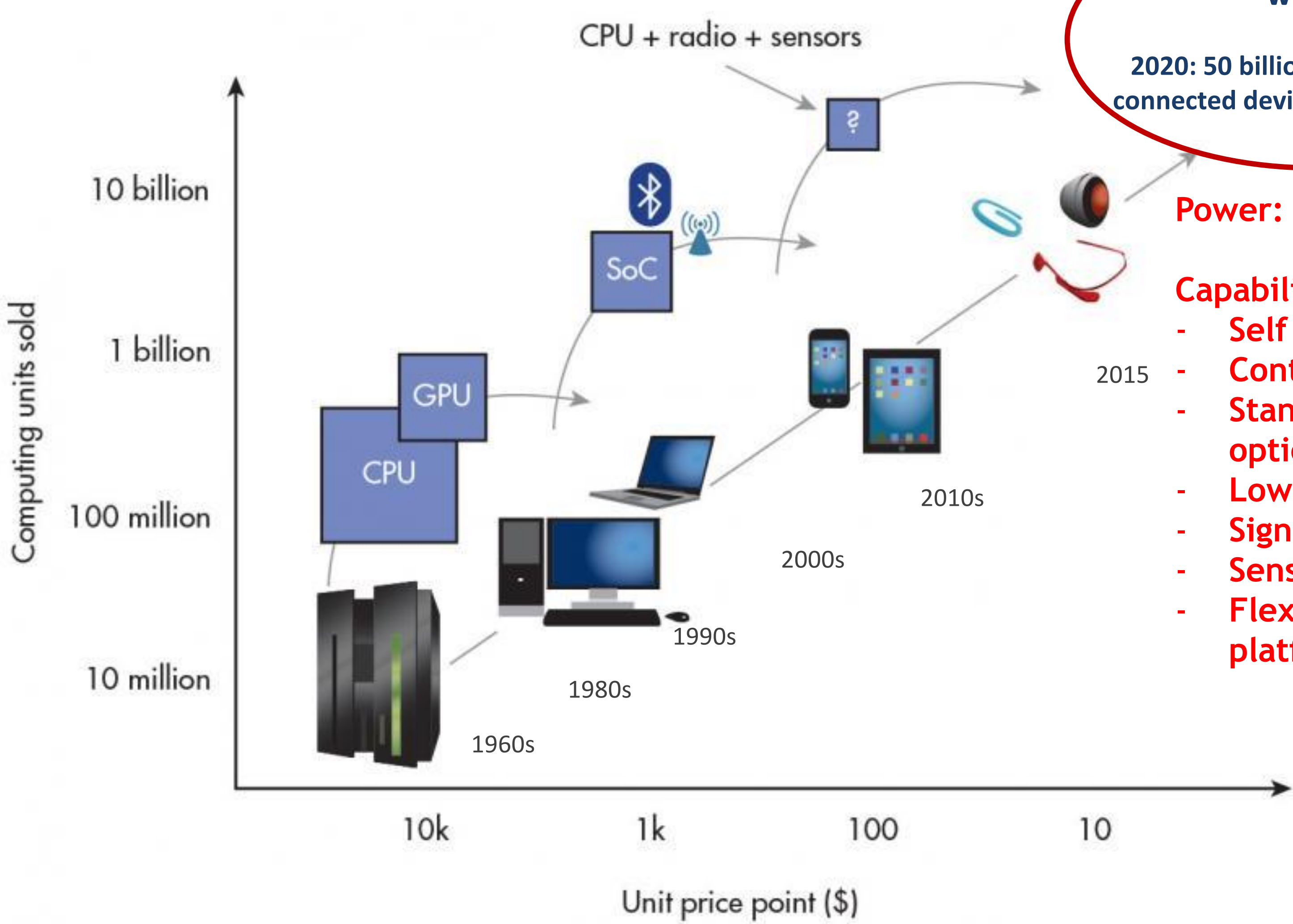
“Ideal” IoT Wireless Sensor



2025: 1 trillion wireless sensors

2020: 50 billion connected devices

Power: <20µW ACTIVE

Capabilities:
- **Self powered**
- **Continuous RF RX**
- **Standard compliant options**
- **Low power TX**
- **Significant processing**
- **Sensor interfaces**
- **Flexible, open platform**

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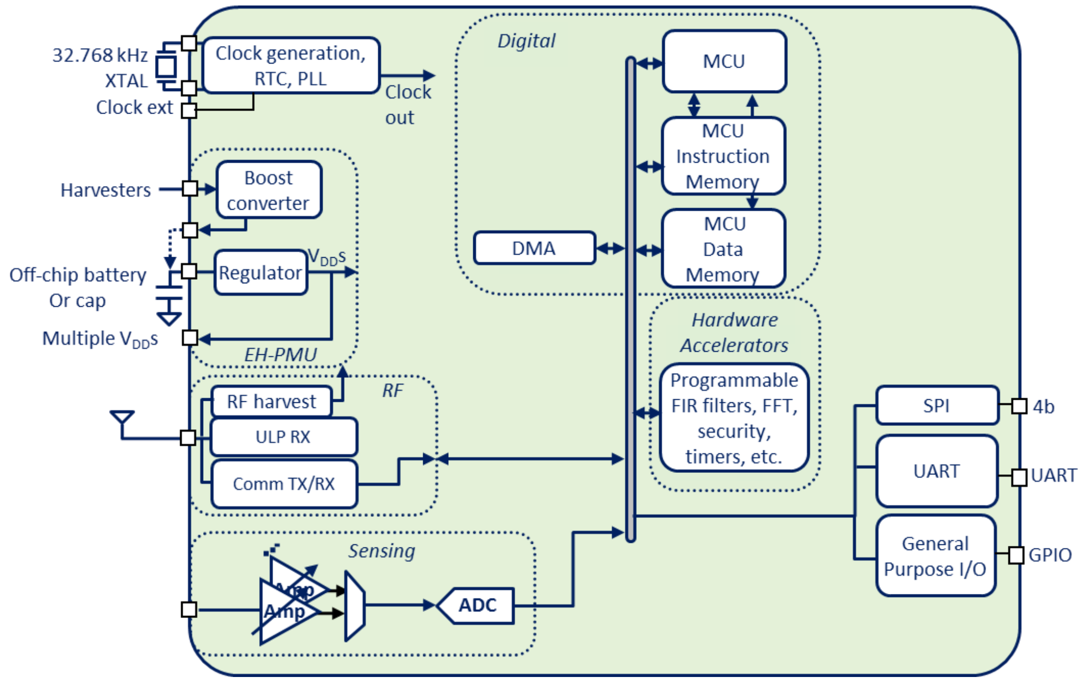
SoC for IoT Sensing

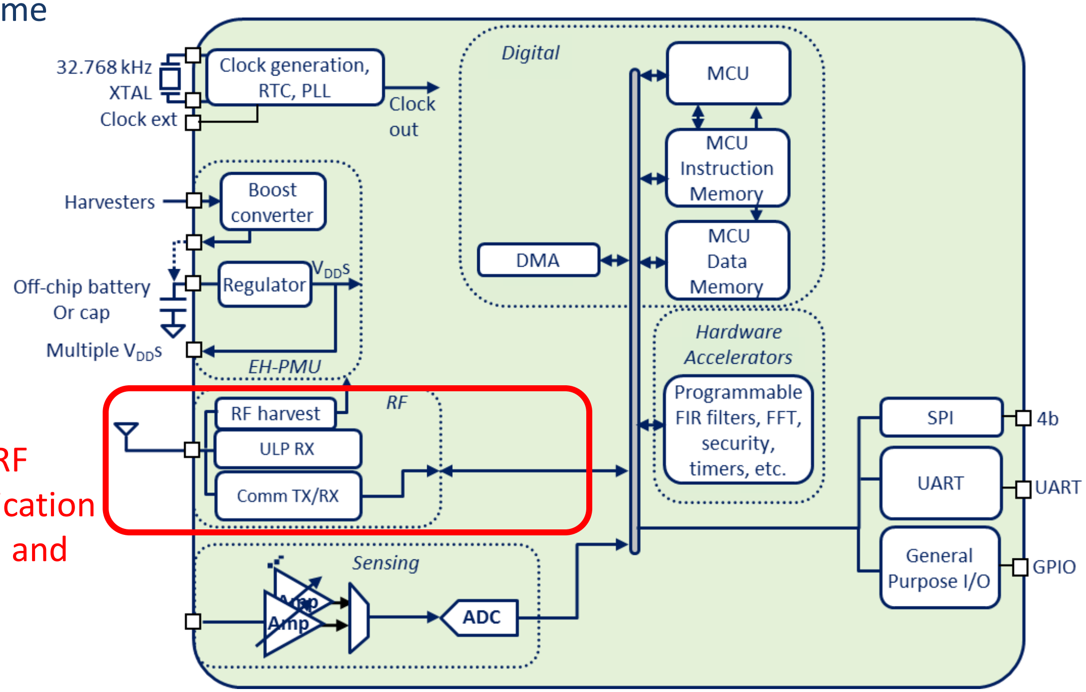


SoC for IoT Sensing

Clock Gen: 32kHz clock. RTC, PLL, counters, time stamping.

Energy Harvesting-Power Management Unit (EH-PMU): harvest from solar, TEG. Boost to 5V. Regulate 3 rails.

Radios: Wakeup RX. RF harvesting. Communication TX/RX with baseband and MAC processing.



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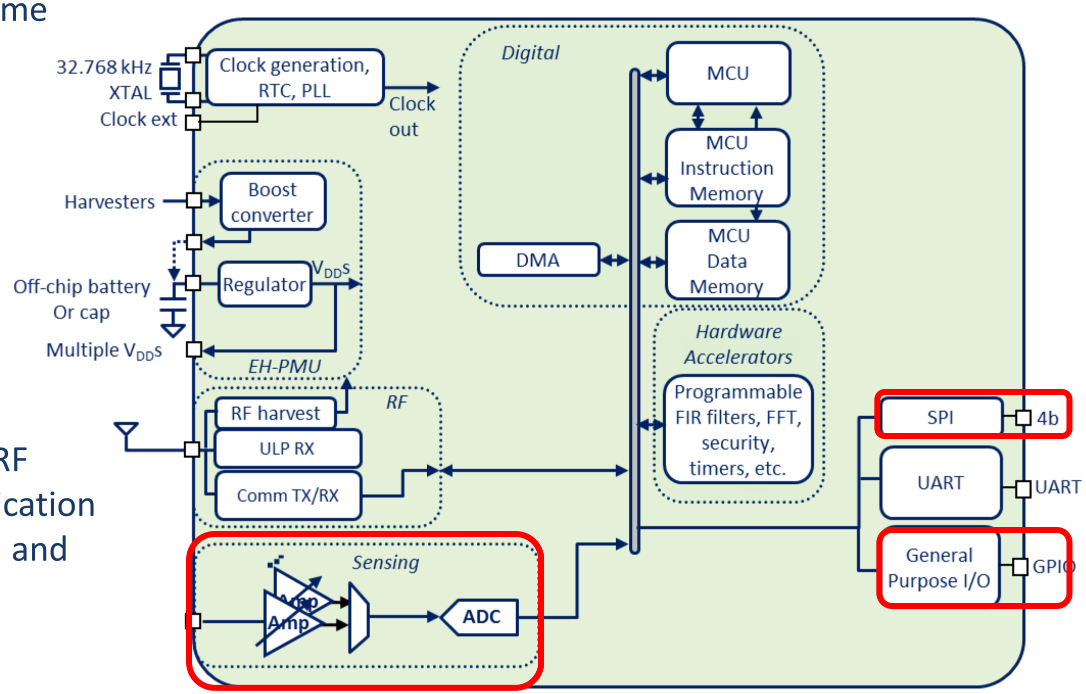

Sensing: Analog front end (AFE), ADC, time stamping, digital interfaces for sensors

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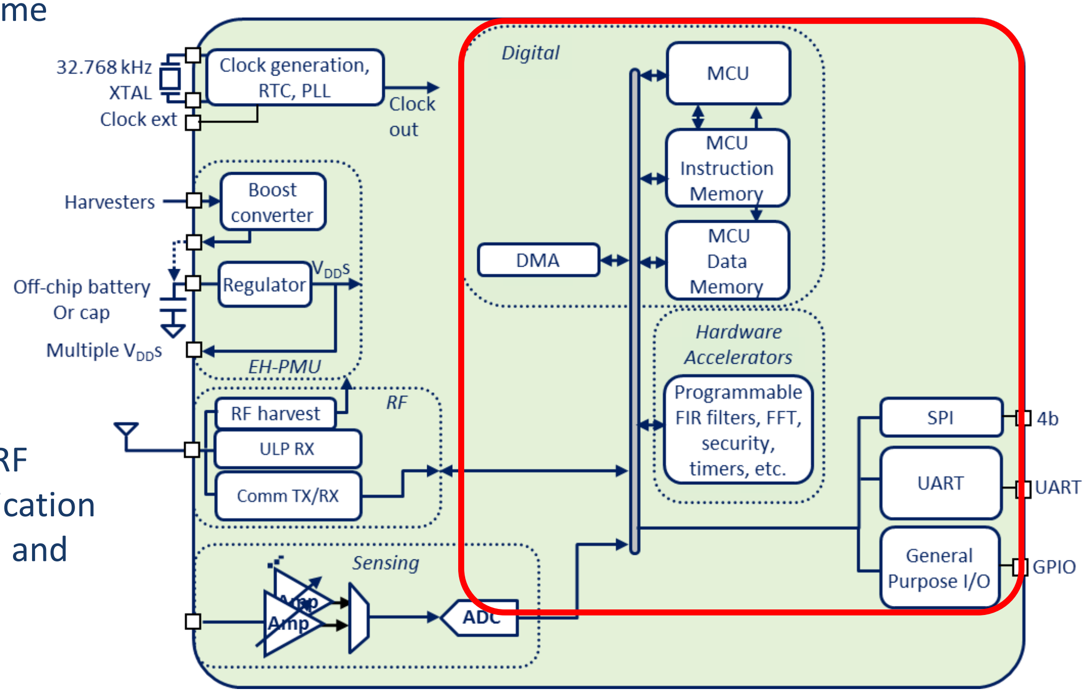

Digital Processing:

MCU: MCU core with dedicated memory for instruction and data, bus, and DMA

Digital I/O: GPIO, UART, SPI, open drain driver, etc. Flexible and programmable.

Digital Accelerators: e.g., FIR, FFT, timers, etc.

Sensing: Analog front end (AFE), ADC, time stamping, digital interfaces for sensors

Conclusion: Enabling a 1T Device IoT

- 1 Trillion IoT devices can ONLY happen WITHOUT batteries
- Self powered operation requires ACTIVE power lower than ~20 μW
- Sub-threshold operation, RF redesign, and extreme system optimization can provide solutions
- <1μW RF wakeup and <20μW SoC are demonstrated

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Thank You

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